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TECHNICAL NOTE

D-1103

EFFECT OF INERT, REDUCING, AND OXIDIZING ATMOSPHERES
ON FRICTION AND WEAR OF METALS TO 1000° F

By Donald H. Buckley and Robert L. Johnson

Lewis Research Center
Cleveland, Ohio

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SUMMARY

Experiments were conducted in inert, reducing, and oxidizing atmospheres to determine their influence on the friction and wear properties of various metals. Nitrogen, argon, forming gas (10 volume percent H₂, 90 volume percent N₂), and various concentrations of oxygen in nitrogen were used. A 3/16-inch-radius hemispherical rider under a load of 1000 grams contacted the flat surface of a rotating disk. The surface speed employed was 35 feet per minute.

The presence of surface oxides is vitally important to the protection of metals in sliding contact. Extremely high friction and excessive wear were encountered in the absence of these oxides. In some instances (electrolytically pure copper), the removal of the surface oxides resulted in mass welding of the specimens in sliding contact. Extremely small quantities of oxygen are sufficient to provide protection of metal surfaces; for example, with 440-C stainless steel, 0.03 volume percent oxygen was found to be adequate.

INTRODUCTION

The presence of oxides on metal surfaces plays a vital role in the friction and wear properties normally observed for these materials. These oxide films act as surface contaminants and prevent intimate metallic contact from occurring when metal surfaces are brought together. Such intimate contact results in strong adhesive forces between the surfaces; and, in many instances, these forces would be sufficient to result in the mass welding of the metal. The work of various investigators (refs. 1 to 3) has indicated very high adhesive forces and friction coefficients for pure metals when denuded of surface oxides.

The need for bearing and seal materials to operate in outer space requires an understanding of what occurs to metal surfaces in the absence of oxides, because the environment beyond the earth's atmosphere is essentially devoid of oxygen and is composed principally of nitrogen and hydrogen at very low pressures (ref. 4). Much work at reduced pressures (vacuum) is being done to simulate these outer-space conditions

and to determine their effects on the friction and wear properties of materials (refs. 5 to 7). The problems associated with the conventional vacuum systems used, however, make space simulation by this simple technique somewhat difficult (ref. 8). Further, no control of oxygen concentration or measure of oxygen partial pressure was included in the reference studies.

The control (or prevention) of surface oxide formation can be achieved by another method, namely, the use of controlled (inert, reducing, or oxidizing) atmospheres at standard pressure conditions. Although the possibility of adsorbed gases on metal surfaces exists with inert or reducing atmospheres, surface oxide formation should not occur. Experimental friction and wear studies in oxygen-deficient and oxygen-free atmospheres should provide a quantitative basis for selection of bearing alloys to be used in outer space.

The object of this investigation was to study the friction and wear properties of various metals in nonreactive atmospheres, reducing atmospheres, and atmospheres with varied amounts of oxygen to establish quantitative threshold values for minimum oxygen concentrations required for inhibiting metal welding. The gases used were nitrogen, argon, forming gas (10 volume percent H_2 , 90 volume percent N_2), and blends of various percentages of oxygen with nitrogen. A very thorough cleaning procedure was used for the experimental gases.

The test specimens used in this investigation consisted of a 3/16-inch-radius hemisphere and a $2\frac{1}{2}$ -inch-diameter flat disk specimen. The tip of the rider contacted the flat surface of the disk with a load of 1000 grams (initial Hertz stress for steel of 150,000 psi). The disk was rotated to obtain a surface speed of 35 feet per minute. Ambient temperatures of 75°, 500°, and 1000° F were used. The metals studied consisted of high-temperature alloys, conventional bearing steel, and electrolytically pure copper. The high-temperature alloys and bearing steel were selected because they were considered to be representative of materials used in high-temperature bearing and seal construction or because they would best show the effects of oxygen. The pure copper was selected on the basis of the available knowledge on the surface reactions of this metal.

MATERIALS AND APPARATUS

Materials

The metals used in this investigation and the composition and hardness of each are presented in table I.

Apparatus

The apparatus used is shown schematically in figure 1(a). The basic elements of the apparatus consist of a rotating-disk specimen ($2\frac{1}{2}$ -in. diam.) and a stationary, hemispherically tipped rider specimen ($\frac{3}{16}$ -in. rad.).

The disk specimen is rotated by means of a varidrive motor unit through a gearbox and spindle assembly. The drive shaft enters the housing of the apparatus through an interlocking labyrinth seal and a bellows-type face seal. The portion of the drive shaft inside the apparatus housing contains a heat shield and the disk specimen, which is held on the shaft by a lock nut. The disk specimens were run at a surface speed of 35 feet per minute. Since chemical reactions are rate processes, the low surface speed is favorable for the formation of protective surface films. Surface film failure occurs most readily at high speeds.

The rider specimen is loaded against the disk surface by means of a retaining arm, which is gimbal and bellows mounted to the apparatus housing. The load is applied to the arm by means of dead weights. Perpendicular to the cable is a linkage connecting the arm with a strain-gage assembly for measuring frictional force.

The test specimens are heated by twelve 650-watt cartridge heaters located in a sealed Inconel housing that fits around the circumferential surface of the disk specimen. The heaters are controlled by a Variac unit and a temperature controller. The controller is operated by a thermocouple located near the point of disk and rider contact. The apparatus was operated at temperatures of 75°, 500°, and 1000° F.

The gases used to provide the various atmospheres were supplied by means of an Inconel tube, at a rate sufficient to provide a positive pressure to the Inconel test chamber (0.7-liter volume) that housed the specimens and heater assembly. Prior to each run, a 15-minute purge period was employed to expel all gases other than those under investigation.

EXPERIMENTAL PROCEDURE

The disk and rider specimens used in this study were finish-ground at 4 to 8 microinches. Before each experiment the disk and rider were given the same preparatory treatment. This treatment consisted of (1) a thorough rinsing with acetone to remove oil and grease, (2) polishing with moist levigated alumina on a soft cloth, (3) a thorough rinsing in tap water followed by distilled water, and (4) a thorough rinsing of the specimens with absolute ethyl alcohol to remove the water. The specimens were then stored in a dessicator. For each experimental (data) point, a new set of specimens was used.

The gases used to provide the experimental atmospheres were very thoroughly cleaned prior to use (fig. 1(b)). The air used in this investigation was obtained from cylinders. Prior to its admission to the test chamber the air was dried to remove moisture by passing it through a series of drying towers: first, a tower containing calcium chloride; second, a concentrated sulfuric acid tower; and third, a tower containing magnesium perchlorate suspended in glass wool. The dried air was then admitted to the apparatus chamber. This same procedure was used for the drying of forming gas.

The gases nitrogen and argon were dried in the same manner as air. However, following the drying cycle, the gases were passed into a Pyrex tube containing hot copper turnings to remove traces of oxygen normally present in cylinder gases.

An alternative purification procedure used with nitrogen in some experimental check runs was to pass the gas through two copper cooling coils (each coil 1/4-in. diam. by 100-ft length) immersed in liquid nitrogen. The two traps were connected in series. The gas was then passed through three Pyrex tubes containing hot copper turnings; the tubes were in series and functioned to remove any oxygen not trapped by the liquid-nitrogen coils. The experimental results obtained with this system checked the results obtained with the procedure previously described. With both systems the oxygen concentration of the inert and reducing gases was less than 0.01 percent, the lower sensitivity limit of the oxygen analyzer. The oxygen concentrations in the various gas atmospheres were monitored in all experiments with the oxygen gas analyzer.

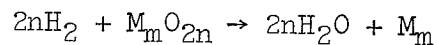
Although direct comparisons of a gas concentration at atmospheric pressure and vacuum are difficult because of such factors as mean free path, preferential pumping in vacuum systems, and surface adsorbed gases, some concept of oxygen concentration can be achieved by a consideration of an equivalent vacuum. For example, 0.01 volume percent oxygen concentration at atmospheric pressure represents the oxygen available in a normal atmosphere reduced in pressure to 2.0 millimeters of mercury absolute. At this reduced pressure, however, the mean free molecular path is greater at low pressures than in a gas at atmospheric pressure, and therefore the number of molecular collisions is decreased at low pressures. The number of oxygen molecules striking the specimen surface in an oxygen-nitrogen mixture at atmospheric pressure should therefore be less than at a pressure of 2.0 millimeters of mercury absolute. The number of oxygen molecules striking the specimen surface per unit time would be near that encountered at a total pressure of 10^{-3} millimeter of mercury absolute (ref. 9).

The apparatus chamber containing the specimens was given various pretreatments prior to an experiment depending on the particular atmosphere employed. When air or forming gas (at 75° F only) was the gaseous environment, a simple 15-minute purge period with the test gas prior to

running was used. In those experiments using forming gas conducted at temperatures of 500° and 1000° F, the forming gas was flowed through the system during the entire purge, preheating, and test period.

For the experiments in which nitrogen or argon was used, a purge of the chamber and specimens with forming gas was employed. With copper, René 41 (nickel-base alloy), Stellite Star J (cobalt-base alloy), and K162B (nickel-bonded carbides), the specimens were heated to a temperature of 1000° F for 10 to 15 minutes in forming gas. The specimens were then cooled down to test temperature in flowing forming gas (for those experiments conducted at 75° and 500° F). This was followed by a 15-minute purge with the gas used in the experiment (nitrogen or argon), and the run then started. For those experiments in which 52100 (iron-base) and 440-C stainless steel (iron-base) were used, the specimens were raised to a temperature of 1400° F for 10 minutes in forming gas prior to the initiation of the experimental gas purge. The room-temperature hardness of 52100 and 440-C after this 10-minute purge at 1400° F was not appreciably affected because of the short time involved. The room-temperature superficial hardness for 52100 was Brinell 550 and, for 440-C, Brinell 480. The reasons for the forming gas purge at elevated temperatures prior to nitrogen or argon experiments were twofold: first, to remove physically adsorbed gases on metal surfaces by chemical reaction and, second, to reduce existing metal oxides.

The reaction of the hydrogen present in forming gas with metal oxides may be expressed by a simple equation:



The concentration of hydrogen necessary for the reduction of various metal oxides can be obtained from the simple thermodynamic relation:

$$\Delta F_H = -2nR_0T \log_n K_H$$

where:

ΔF_H change in free energy of formation per gram mole of M_mO_{2n}

n mole concentration

R_0 gas constant

T temperature, °K

K concentration of $\frac{\text{products}}{\text{reactants}}$ for equilibrium conditions

An examination of the concentration ratios $[H_2O]/[H_2]$ at various temperatures gives some concept of the temperatures needed for the

reduction of various metal oxides by hydrogen. The data for reduction of some of the oxides of alloying elements used in the specimens of this investigation were obtained from reference 9 and are presented in figure 2. The oxides of copper, cobalt, and nickel are relatively easily reduced at moderate temperatures by hydrogen. The reduction of iron oxides is more difficult to achieve. With chrome oxide at 1200° K, the H₂O concentration must be less than 1 part in 7400 of hydrogen in order for reduction of Cr₂O₃ to occur.

In the experiments reported herein, the rider was loaded against the disk specimen with a 1000-gram load for all metal combinations except copper. A copper rider specimen under 1000 grams load would result in a complete wearing away of the rider radius in minutes. A 500-gram load was therefore used with copper specimens. All the friction and wear data were obtained at a surface speed of 35 feet per minute. The duration of each experiment was normally 1 hour. Some copper experiments were terminated after 30 minutes because of excessive wear of the rider specimens. In those instances where mass welding of the specimens occurred, the experiments were stopped after even shorter periods of time. Wear was measured as volume loss to the rider specimens, and in some instances wear to the disk surface was also recorded. X-ray diffraction, electron diffraction, and microhardness tests were employed to study surface films and transformations.

RESULTS AND DISCUSSION

Air Atmosphere

Friction and wear experiments were conducted with a conventional bearing steel 52100, a stainless steel 440-C, Stellite Star J (cobalt-base alloy), René 41 (nickel-base alloy), and K162B (mixed nickel-bonded titanium and columbium carbides) in air at temperatures of 75°, 500°, and 1000° F. The results obtained in these experiments are presented in figure 3 (which also gives the results obtained in nitrogen, argon, and forming gas).

The friction coefficient for the ferrous alloys decreased with increasing temperature in air. The wear of 52100 steel increased with temperature. The wear value obtained at 500° F was seven times the wear result obtained at room temperature; increasing the ambient temperature to 1000° F resulted in an additional threefold increase in the wear obtained for 52100 steel. These results with 52100, however, may be explained in terms of loss in hardness for this particular alloy at elevated temperatures. Stellite Star J also exhibited an increase in wear with an increase in ambient temperature. In general, temperature change seemed to have very little effect on the wear properties of the other alloys.

Inert Atmosphere

Nitrogen. - Figure 3 presents the friction and wear data for the same metals in a nitrogen atmosphere. For all the metals investigated, a marked increase in friction over the results obtained in air was observed. This increase occurred at all three temperatures: 75°, 500°, and 1000° F. The increase indicates the effect that oxygen reduction has on metals in sliding contact. In the absence of surface oxides the friction coefficients increase rather sharply. The contrast of friction coefficients obtained in air and nitrogen at 1000° F for 440-C stainless steel can be seen in figure 4.

There is, however, in a nitrogen atmosphere the possibility of nitride formation with ferrous-base alloys possessing chromium and/or aluminum in their structures. The possible formation of nitrides was suspected for 52100 steel sliding on itself. X-ray diffraction, electron diffraction, and microhardness tests were made to determine whether nitrides had formed in the wear areas. With X-ray diffraction, the only pattern obtained was that of the base metal, which indicated that, if a film were present, it was too thin to detect by X-ray diffraction. The next analytical tool employed was electron diffraction. The results obtained indicated in some instances the presence of an amorphous film, and in others gave a pattern that could not be positively identified with any available standard. The only indication of nitride formation was obtained with a microhardness scratch test. Scratches were made across the wear area of disks run in three atmospheres: vacuum, air, and nitrogen. In both vacuum and air environments a scratch across the entire wear area was discernible. In nitrogen, however, the scratch disappeared in the wear area, which indicated a region of increased hardness. This hardened area is assumed to be nitrified.

Argon. - Friction and wear experiments were conducted in argon, an inert atmosphere, and the results obtained are shown in figure 3. Both friction and wear were higher than encountered in an oxidizing atmosphere.

Reducing Atmosphere

The friction coefficients and wear values obtained for the various alloys in forming gas, a reducing atmosphere, are also presented in figure 3. With Rene 41 and K162B, the friction and wear values obtained in forming gas were generally higher than obtained in any of the previously considered atmospheres. However, for the ferrous alloy 52100 at 1000° F the maximum friction and wear were obtained in argon. Since forming gas is 90 percent nitrogen, the possibility of nitride formation with these alloys again exists. In reference 8 a friction experiment was conducted with 52100 sliding on 52100 in vacuum. Liquid helium was used for the cryogenic pumping of the system. Liquid helium will condense all gases except helium. Under such experimental conditions, where neither oxides

nor nitrides could readily form, a coefficient of friction of 5.0 was obtained for 52100. This high friction was followed by a welding together of the specimens.

The wear values given in figure 3 were obtained by measuring wear volume of the rider specimen. In order to determine the relative wear to the disk specimens, surface profile traces were made across the disk wear area for 440-C sliding on itself at 1000° F in all four atmospheres. Typical tracings are reproduced in figure 5. The wear to the disk was least in air and reached a maximum in forming gas. The center of the wear track obtained in forming gas shows a "buildup" indicating metal transfer between rider and disk.

Oxidizing Atmospheres

Since surface oxides play such an important role in the friction and wear properties normally observed for metals, it was decided to explore the influence that various percentages of oxygen in the atmosphere would have on the formation of these oxides. Friction and wear experiments were therefore conducted with 440-C stainless steel sliding on itself at 75°, 500°, and 1000° F in gases with O₂ concentrations of >0.01 to 21 volume percent. The atmospheres in which the experiments were conducted consisted of various percents of purified air blended with nitrogen.

The friction and wear results obtained in these experiments with 440-C stainless steel and varying percentages of oxygen in nitrogen are presented in figure 6. It is interesting to note that, at temperatures of 500° and 1000° F with an oxygen concentration of 0.03 volume percent, sufficient surface oxide is formed at the sliding interface to result in a friction coefficient closely approximating that obtained in air. These results at first seemed to indicate that the presence of chromium in the alloy, with its strong affinity for oxygen, accounted for the low oxygen concentration necessary to obtain protective surface oxides. The same experiments were therefore repeated at an oxygen concentration of 0.03 volume percent with the slider material changed to 1020 mild steel. The experiments were run at 1000° F, and the friction coefficient decreased from 0.78 in >0.01 percent oxygen (100 percent nitrogen) to 0.26 in an atmosphere containing 0.03 volume percent oxygen. These results indicate that the low friction coefficient in 0.03 volume percent oxygen may be associated with the formation of the lower iron oxides (FeO and Fe₃O₄, refs. 10 and 11); these results also indicate that iron oxides form at very low oxygen concentrations. A similar result was obtained with 52100 steel in reference 8, where the ambient pressure was varied. The amount of oxygen necessary for the formation of protection surface oxides will vary with sliding velocity. The oxygen concentration will increase with increased sliding velocities.

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Friction and wear data, obtained with alloys containing a number of elemental constituents in an oxidizing atmosphere, may be profoundly influenced by the presence of minor alloying elements. Though some of these elements may represent only small percentages of the alloy composition, their strong affinity for oxygen results in high concentrations of the oxides of these elements in the alloy surface film. Chromium and aluminum are good examples of such alloying elements. In order to avoid this problem, some friction and wear experiments were conducted with electrolytically pure copper sliding on itself. The surface oxides of this metal and their influence on friction and wear have been studied qualitatively (refs. 12, 13, and 14).

Quantitative experiments were conducted in air, nitrogen, argon, and forming gas using copper as the metal under investigation. The runs were made at 75°, 500°, and 1000° F. The results obtained are presented in figure 7. In those experiments made in air, the friction coefficient and wear were found to decrease with increasing temperature. The cupric oxide (CuO) has a very pronounced effect in the reduction of friction and wear of pure copper. In both argon and nitrogen the friction coefficients obtained for copper at 500° and 1000° F were very much higher than were obtained in air. At 75° F the friction values for copper in air, argon, and nitrogen were quite similar. The film of oxide formed on copper in air at room temperature is extremely thin (100 Å) and probably very easily ruptured, which results in considerable intimate metal-to-metal contact. The wear for copper on copper in argon and nitrogen was generally higher than that in air. At 1000° F, the wear of the copper rider in nitrogen and argon was so severe that the radius had completely worn away.

The experiments conducted with copper in forming gas (fig. 7) gave extremely high friction and wear. The friction and wear increased with increase in ambient temperature. At 75° F the friction coefficient for copper sliding on copper was approximately 2.0, while at 1000° F the friction was extremely high (>11.0) and mass welding of the specimens occurred (fig. 7). Figure 8 shows the rider specimen with its interface welded solidly to the disk specimen after disassembly. Under such conditions shearing of these welds during sliding resulted in friction coefficients of 11.0 repeatedly being measured, and momentary values as high as 18.0 were recorded.

The copper surfaces were so responsive to changes in atmosphere that alternate forming gas - air experiments were made. During these experiments the atmosphere was changed from forming gas to air during the course of a run, with the coefficient of friction changing from 11.0 in forming gas to 0.5 in air; these results were reversible.

The marked differences in wear of copper surfaces with and without the benefit of oxides can be seen in figure 9. The photographs indicate

the reduction in wear where surface protection is afforded by the oxides of copper.

The welding of materials in the absence of oxygen can be accomplished with metals other than copper. Friction experiments conducted with aluminum and silver in forming gas at 1000° F resulted in the welding of the metals. Friction coefficients as high as 10.0 were also obtained in an earlier investigation with nickel sliding on nickel in forming gas (ref. 15).

Oxygen concentration experiments were made at 1000° F with copper to determine the quantity of oxygen necessary to provide adequate protective surface films. Various percentages of oxygen were blended with both argon and nitrogen. The results obtained in these experiments are presented in figure 10. With the oxygen-nitrogen mixtures, an oxygen concentration of about 2.2 volume percent was necessary to obtain friction coefficients similar to that obtained in air. When oxygen was blended with argon, an oxygen concentration of <1.0 volume percent was necessary to obtain the same result. The difference in oxygen requirement may be due to the possible formation of oxygen-nitrogen compounds (e.g., NO, N₂O, and NO₂) when oxygen is blended with nitrogen. The formation of such gaseous compounds would reduce the amount of oxygen available to react with the copper surfaces. In addition, the intermolecular collisions in gases inhibit the number of active gas molecules striking a metal surface. These inter-gas molecular collisions will depend on the velocity of the gas molecules. The argon gas atom moves at a much slower velocity than the nitrogen and can therefore be expected to undergo fewer collisions with oxygen molecules. As a result, a greater number of oxygen molecules can be expected to strike the metal surface (specimen) in the oxygen-argon system. Changing the sliding velocity can be expected to alter the oxygen concentration necessary to form the protective surface oxides.

SUMMARY OF RESULTS

The experimental results obtained in this study of the influence of inert, reducing, and oxidizing atmospheres on the friction and wear properties of materials are summarized as follows:

1. Friction and wear properties of metals and bearing alloys are extremely sensitive to oxygen availability. The minimum oxygen concentrations required for formation of protective surface films varies with different metals and should be increased by greater sliding velocities. The formation of a protective surface oxide for 440-C stainless steel at 1000° F can be accomplished with as little as 0.03 volume percent O₂, while copper requires about 2.2 volume percent at the same temperature.

The required oxygen concentrations for the formation of these protective surface oxides vary also with other constituents of the atmosphere (<1.0 volume percent O₂ in argon at 1000° F).

2. With 52100, lower friction was obtained in nitrogen than in argon. This may be attributed to the formation of nitrides.

3. Pure metals such as copper, silver, aluminum, and nickel weld readily at 1000° F in inert and reducing atmospheres.

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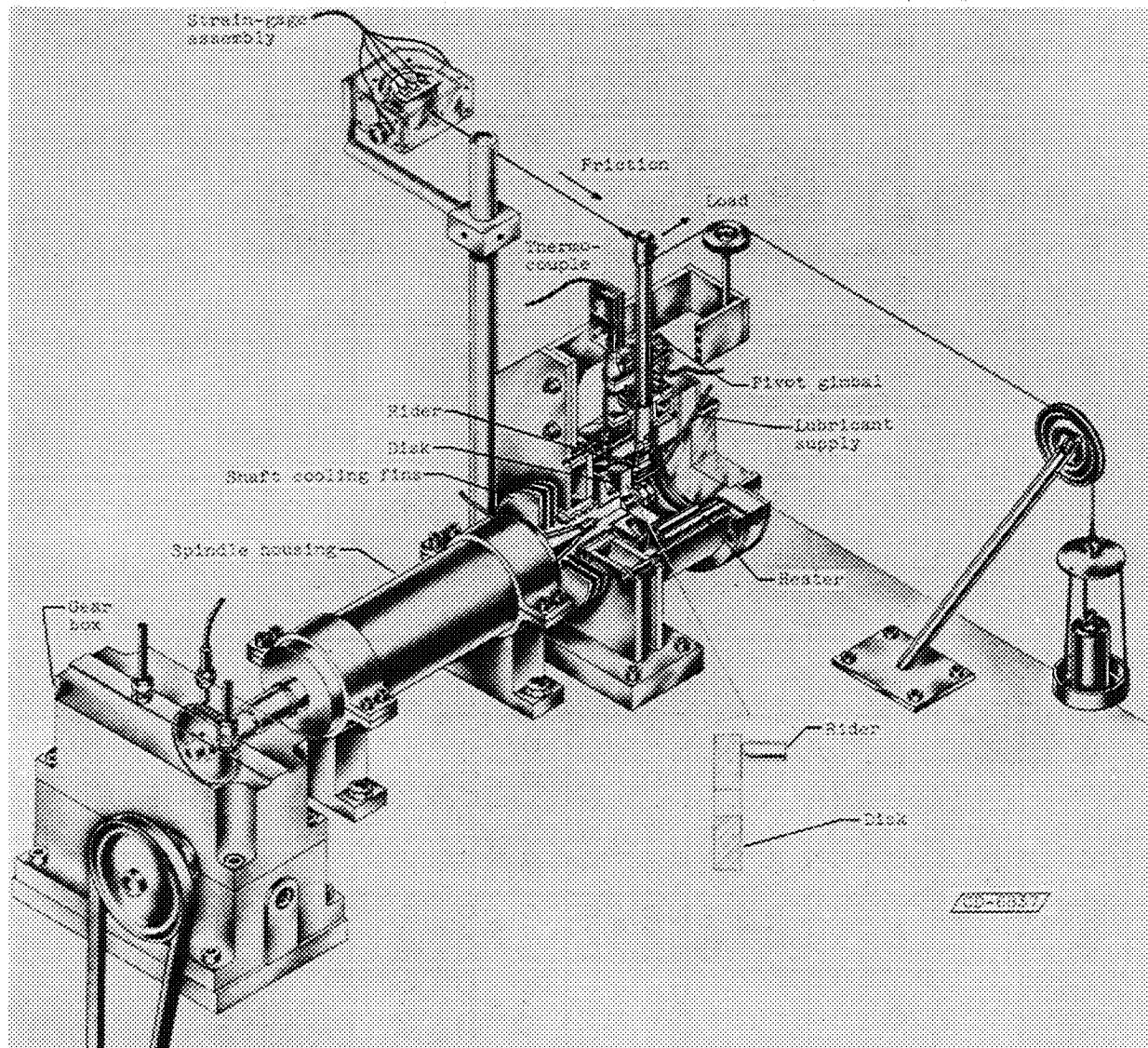
National Aeronautics and Space Administration
Cleveland, Ohio, August 17, 1961

REFERENCES

1. Bowden, F. P., and Hughes, T. P.: The Friction of Clean Metals and the Influence of Adsorbed Gases. The Temperature Coefficient of Friction. Proc. Roy. Soc. (London), ser. A, vol. 172, no. 949, Aug. 3, 1939, pp. 263-279.
2. Bowden, F. P., and Young, J. E.: Friction of Clean Metals and the Influence of Adsorbed Films. Proc. Roy. Soc. (London), ser. A, vol. 208, no. 1094, Sept. 7, 1951, pp. 311-325.
3. Bowden, F. P., and Rowe, G. W.: The Adhesion of Clean Metals. Proc. Roy. Soc. (London), ser. A, vol. 233, no. 1195, Jan. 10, 1956, pp. 429-442.
4. Atkins, J. H., et al.: Effects of Space Environment on Materials. National Research Corp., Aug. 15, 1960.
5. Johnson, Virgil R., Vaughn, George W., and Lavik, Melvin T.: Apparatus for Friction Studies at High Vacuum. Rev. Sci. Instr., vol. 27, no. 8, Aug. 1956, pp. 611-613.
6. Hansen, S., Jones, W., and Stephenson, A.: Research Program on High Vacuum Friction. Pub. 1023, Litton Ind., Inc., Mar. 30, 1959.
7. Freundlich, M. M., and Hannan, C. H.: Problems of Lubrication in Space. Lubrication Eng., vol. 17, no. 2, Feb. 1961, pp. 72-77.
8. Buckley, D. H., Swikert, M., and Johnson, R. L.: Friction, Wear, and Evaporation Rates of Various Materials in Vacuum to 10^{-7} mm Hg. Paper presented at ASLE-ASME Lubrication Conf., Chicago (Ill.), Oct. 1961.

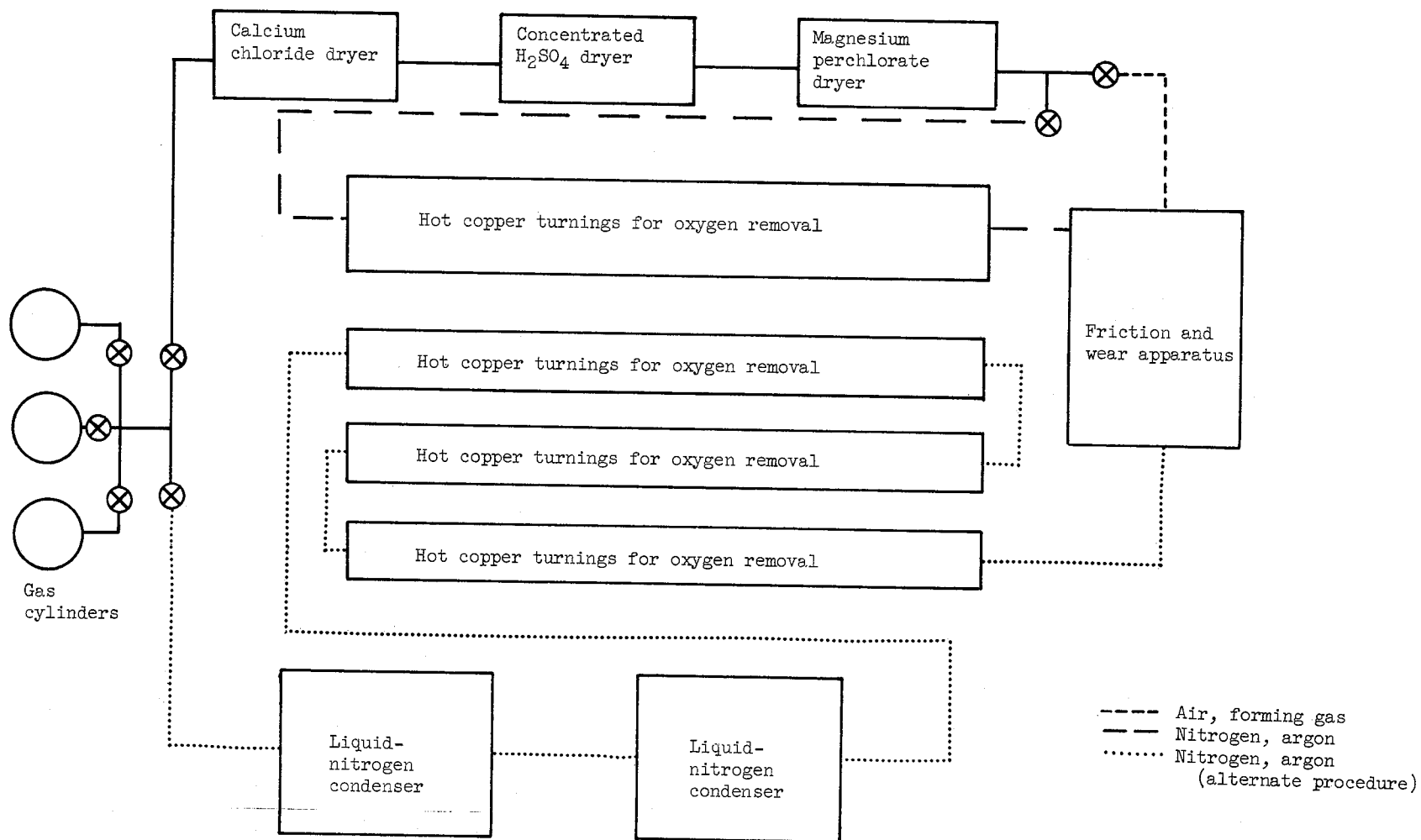
9. Dushman, S.: Vacuum Technique. John Wiley & Sons, Inc., May 1955.
10. Bisson, Edmond E., Johnson, Robert L., and Swikert, Max A.: Friction, Wear, and Surface Damage of Metals as Affected by Solid Surface Films: A Review of NACA Research. Paper presented at Inst. Mech. Eng. Conf. on Lubrication and Wear, Oct. 1-3, 1957.
11. Ernst, Hans, and Merchant, M. Eugene: Chip Formation, Friction and Finish. Cincinnati Milling Machine Co., Aug. 24, 1940.
12. Johnson, R. L., Swikert, M. A., and Buckley, D. H.: High Temperature Lubrication in Reactive Atmospheres. Corrosion, vol. 16, no. 8, Aug. 1960, pp. 101-104.
13. Peterson, M. B., Florek, J. J., and Murray, S. F.: Consideration of Lubricants for Temperatures Above 1000° F. Trans. ASLE, vol. 2, no. 2, May 1960, pp. 225-234.
14. Bowden, F. P., and Tabor, D.: The Friction and Lubrication of Solids. Clarendon Press (Oxford), 1950, pp. 147-151.
15. Buckley, D. H., and Johnson, R. L.: The Influence of Silicon Additions on Friction and Wear of Nickel Alloys at Temperatures to 1000° F. Trans. ASLE, vol. 3, no. 1, Apr. 1960, pp. 93-100.

^aTi and Cb are present as mixed carbides.



(a) High-temperature friction apparatus.

Figure 1. - Experimental setup.



(b) Gas purification systems.

Figure 1. - Concluded. Experimental setup.

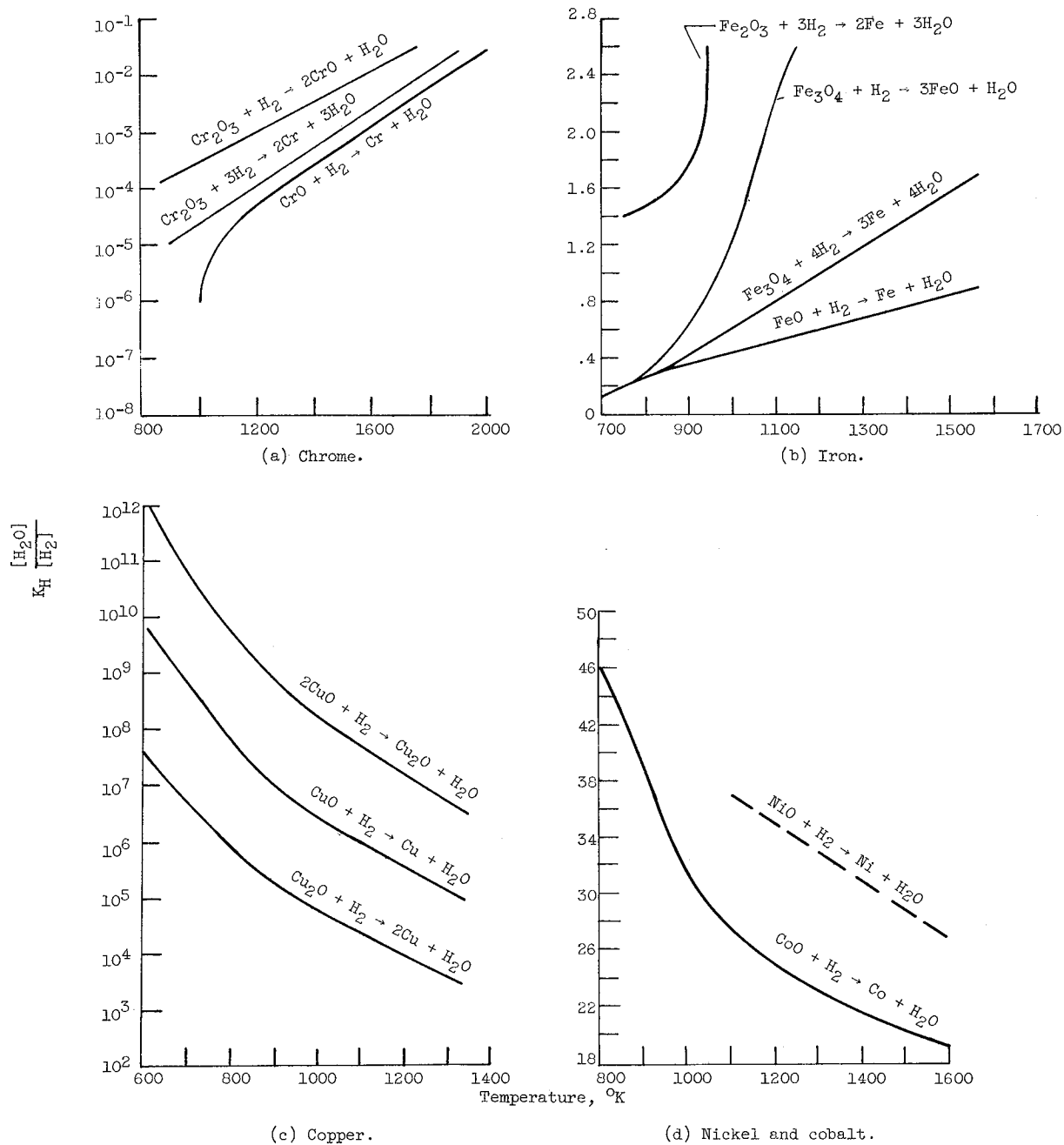


Figure 2. - Equilibrium concentration ratios for reduction of various metal oxides by hydrogen.

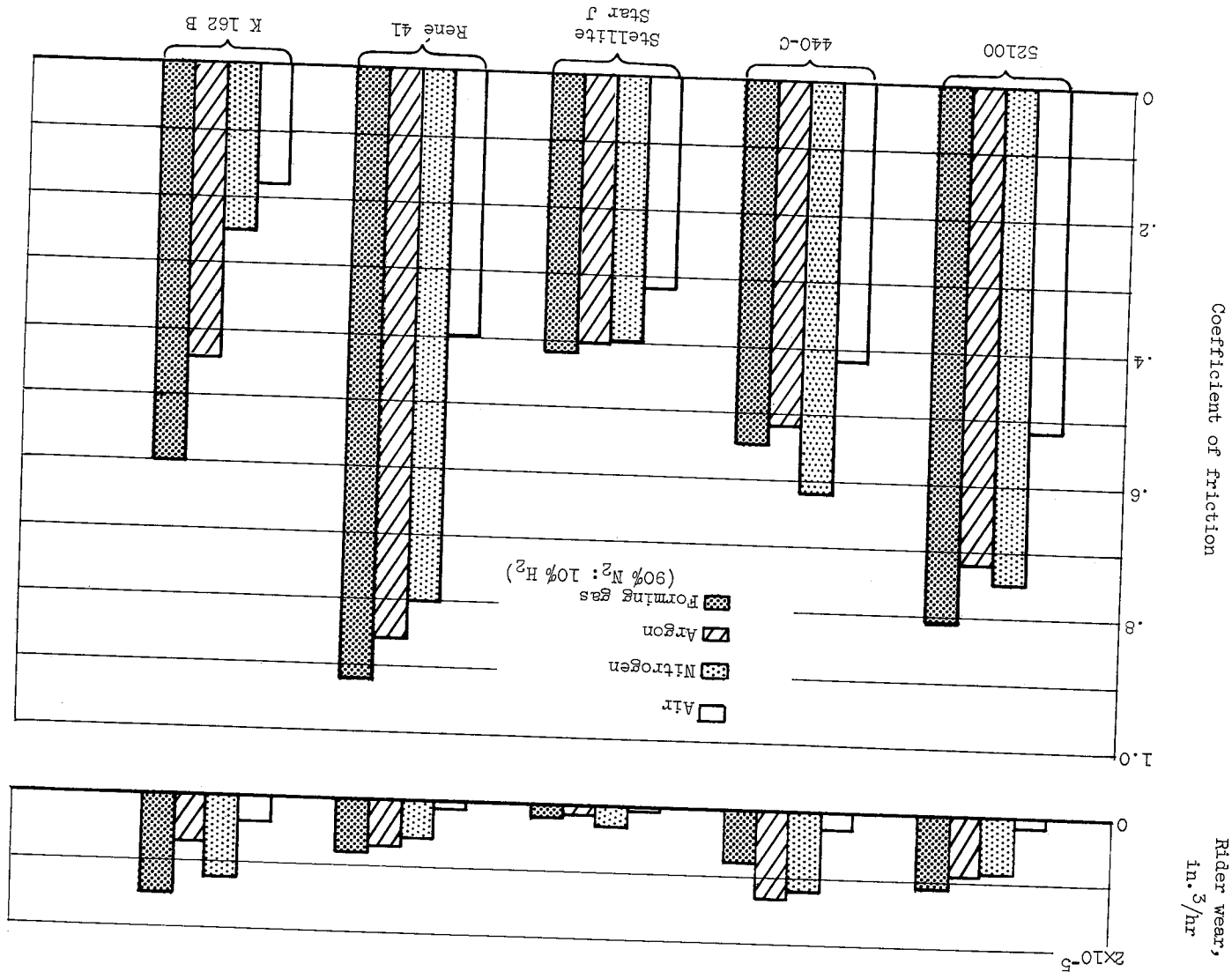
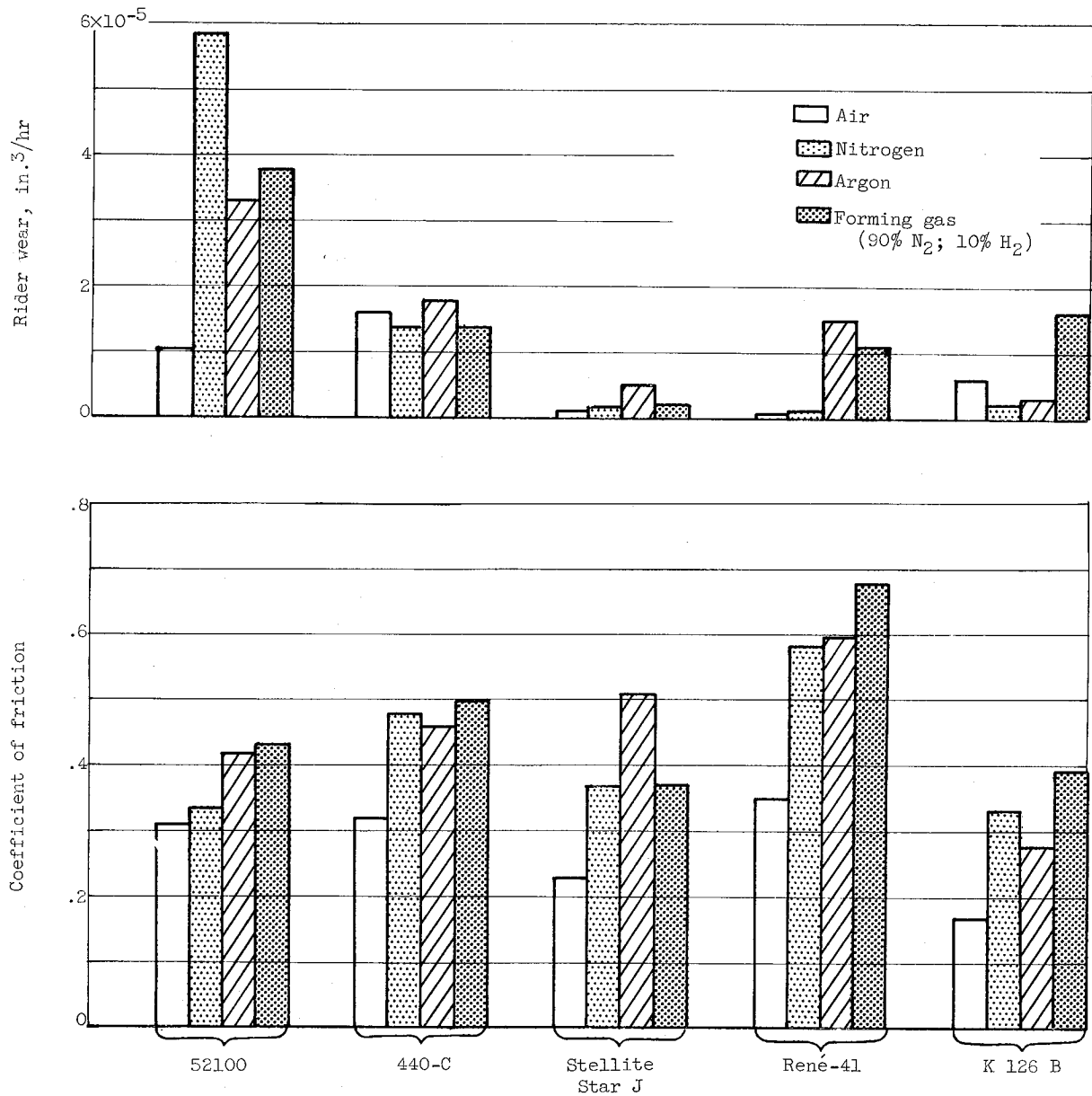


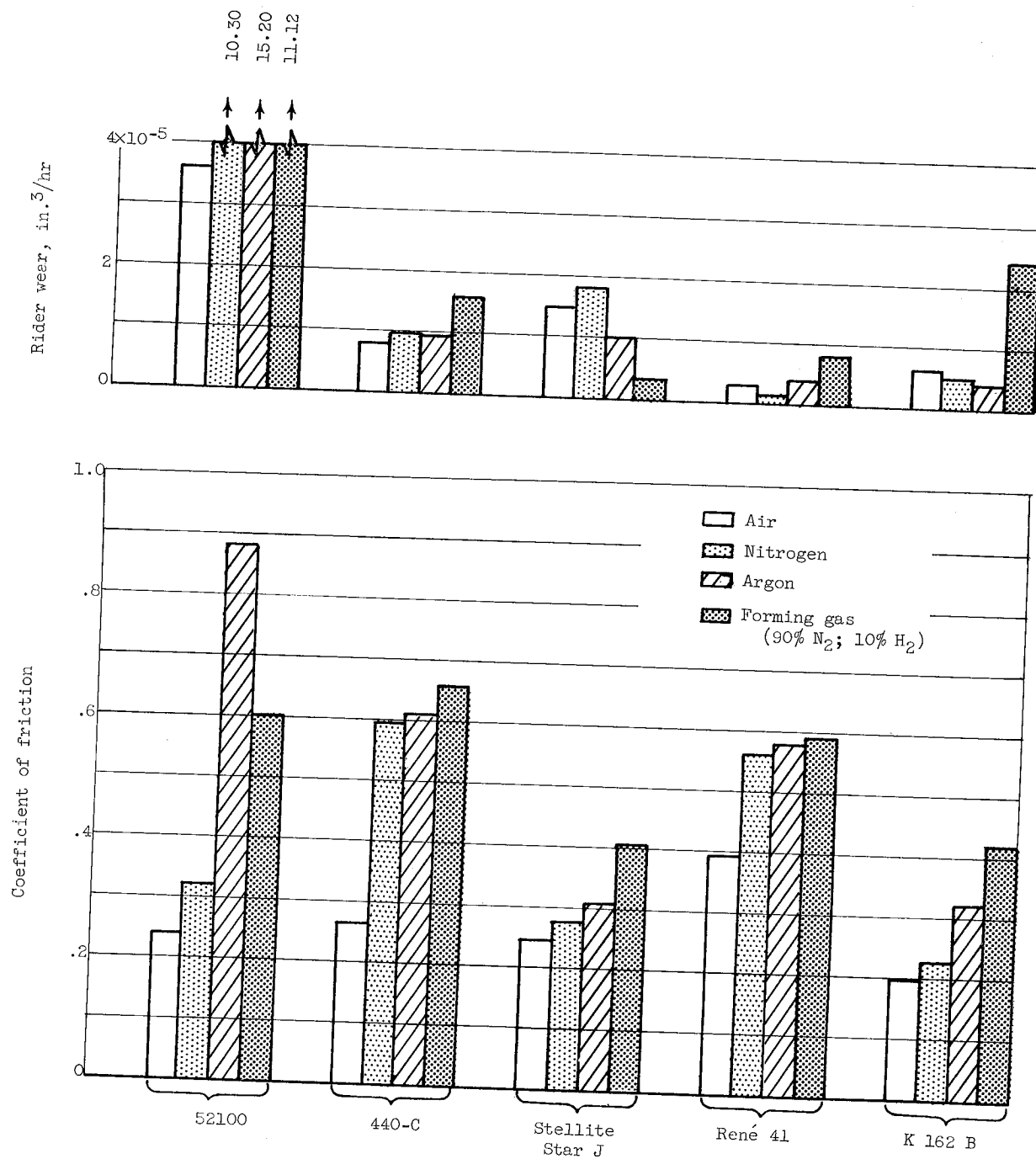
Figure 3. - Friction and wear of various materials in four gaseous environments. Sliding velocity, 35 feet per minute; load, 1000 grams; duration, 1 hour.

(a) Temperature, 75° F.



(b) Temperature, 500° F.

Figure 3. - Continued. Friction and wear of various materials in four gaseous environments. Sliding velocity, 35 feet per minute; load, 1000 grams; duration, 1 hour.



(c) Temperature, 1000° F.

Figure 3. - Concluded. Friction and wear of various materials in four gaseous environments. Sliding velocity, 35 feet per minute; load, 1000 grams; duration, 1 hour.

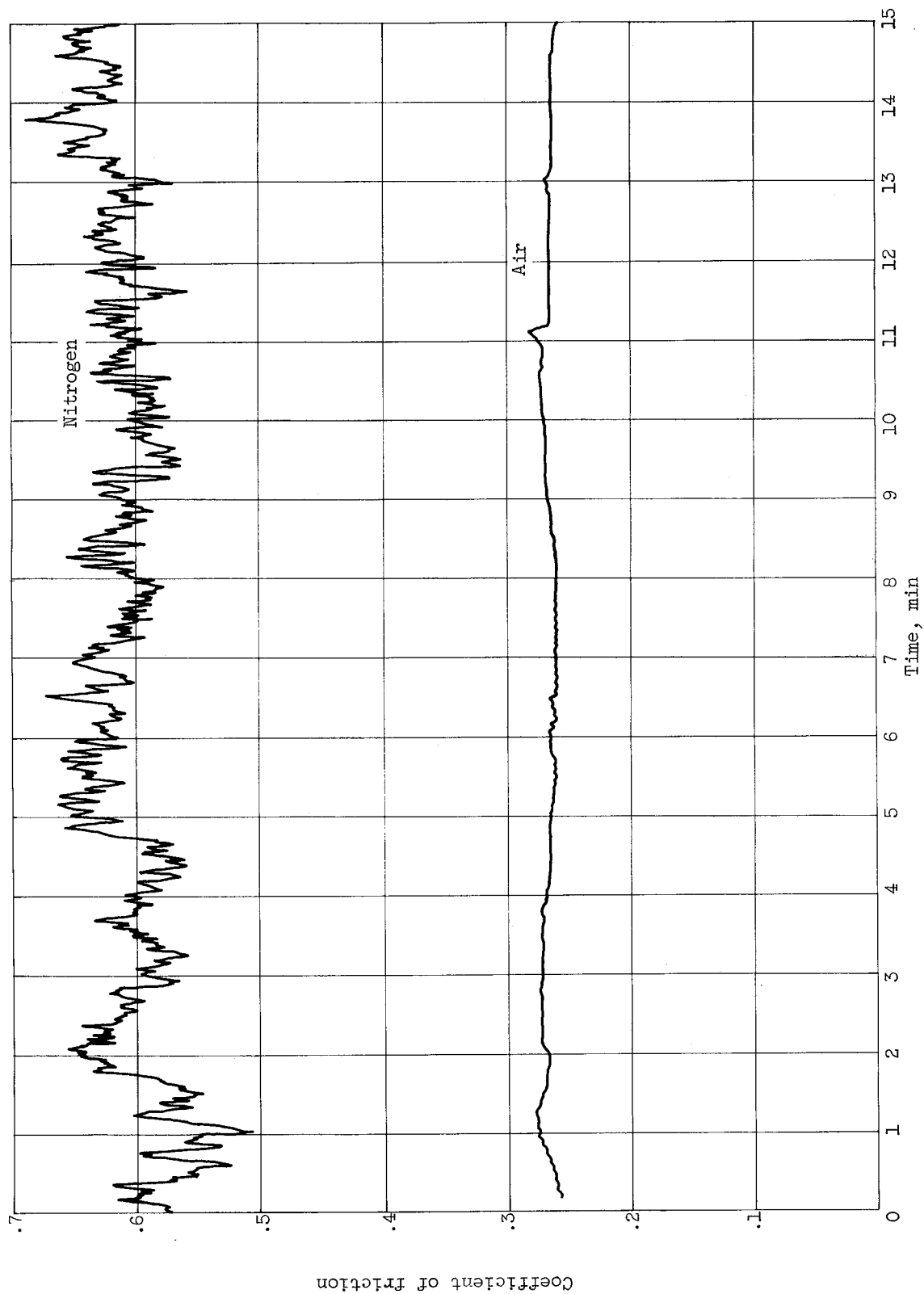
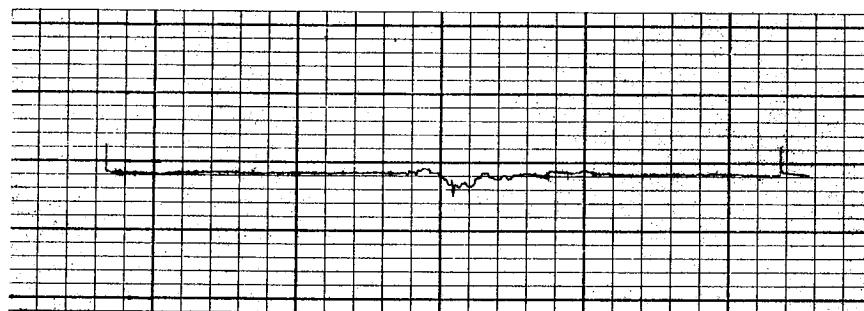
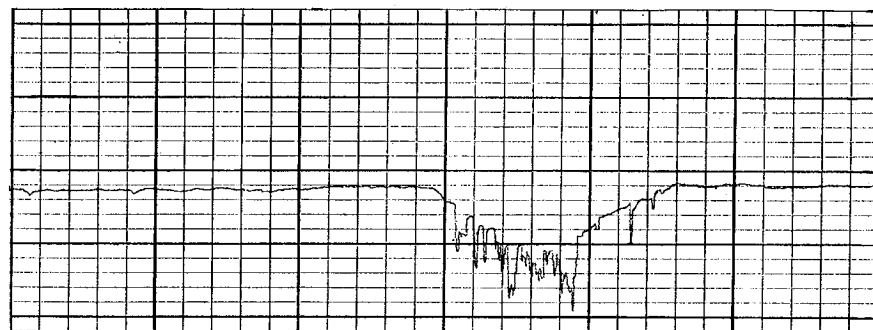


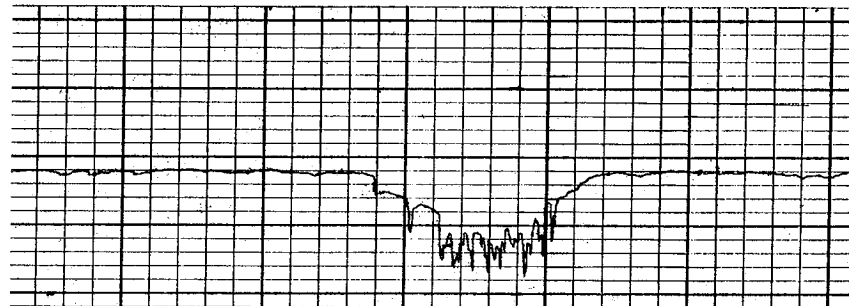
Figure 4. - Coefficient of friction for 440-C sliding on 440-C stainless steel in nitrogen and air. Sliding velocity, 35 feet per minute; load, 1000 grams; temperature, 1000 °F.



(a) Air.



(b) Nitrogen.



(c) Argon.

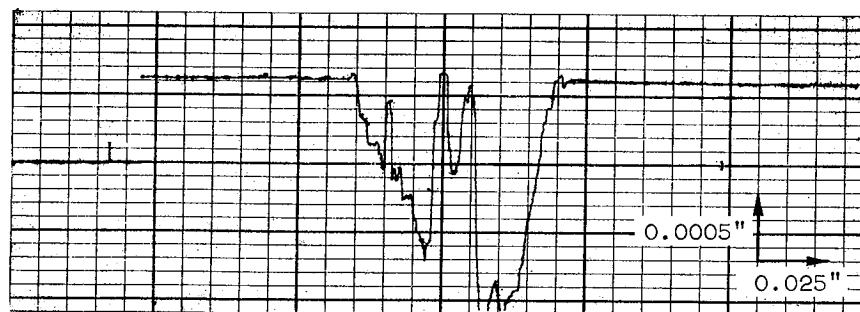
(d) Forming gas (10% H_2 ; 90% N_2).

Figure 5. - Wear profiles of 440-C stainless steel disks.
 Rider, 440-C stainless steel. Sliding velocity, 35 feet
 per minute; load, 1000 grams; duration, 1 hour, temper-
 ature, 1000° F.

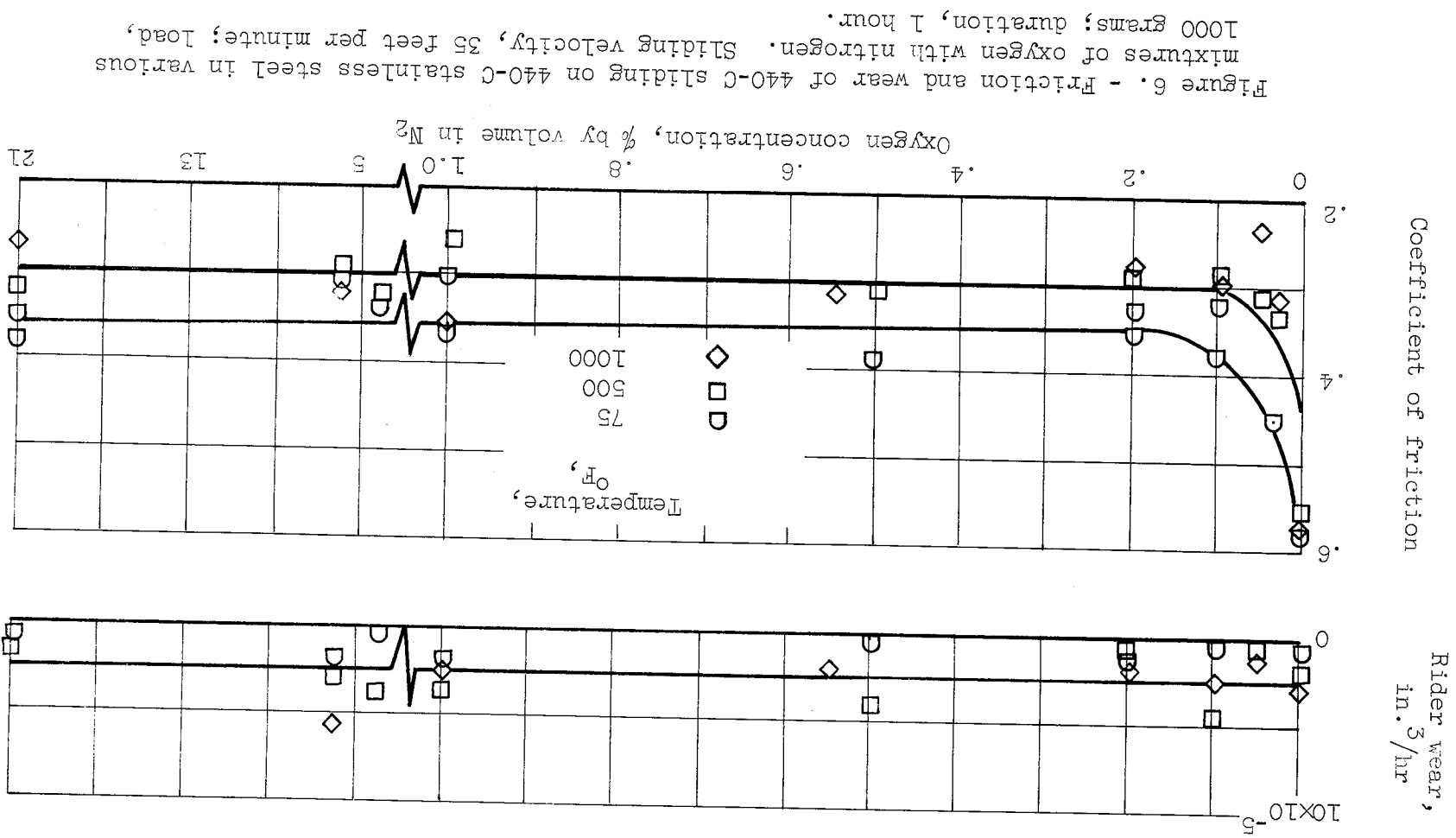
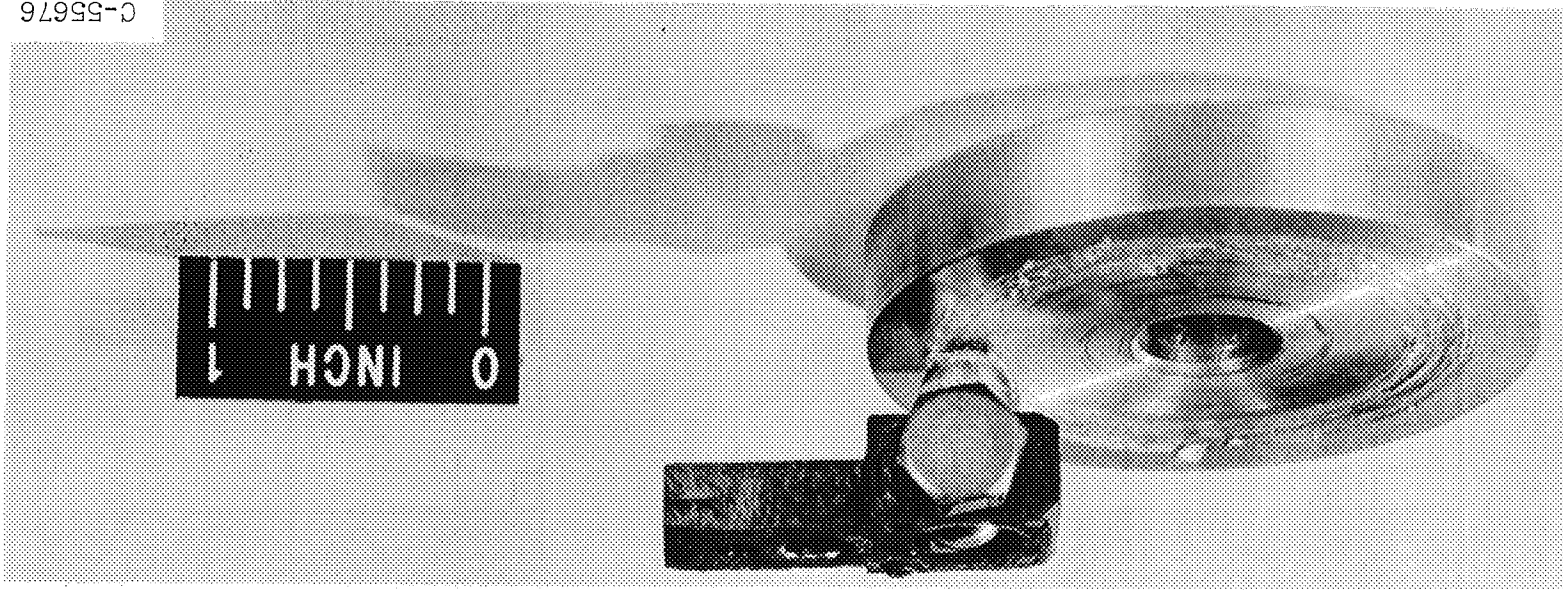




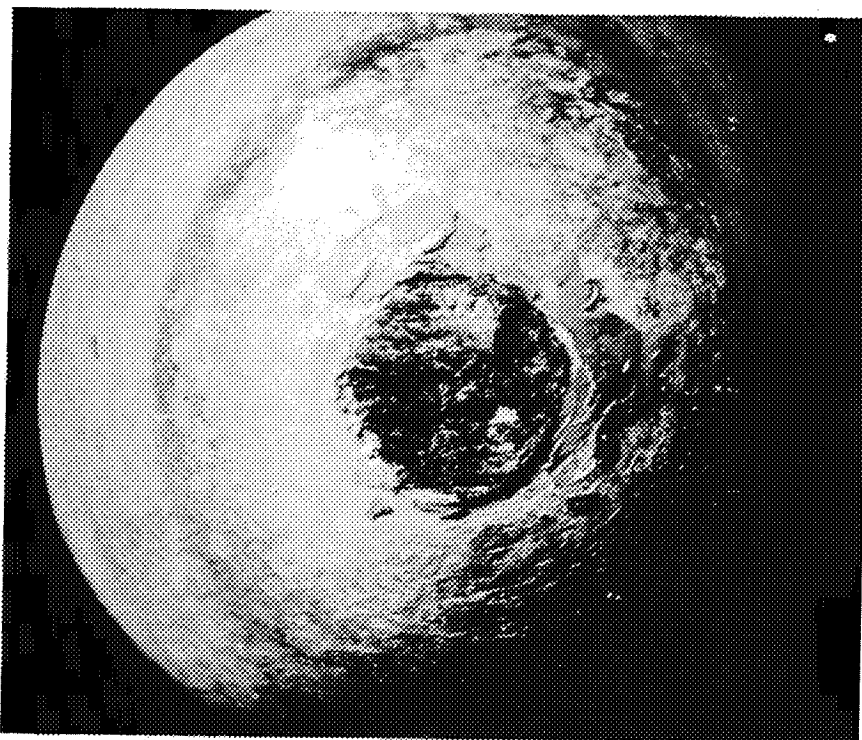
Figure 7. - Coefficient of friction and wear of electrolytic copper sliding on electrolytic copper in various atmospheres. Sliding velocity, 35 feet per minute; load, 500 grams; duration, 1 hour.

Figure 8. - Copper disk and rider specimen welded in a forming gas atmosphere at 1000° F. Sliding velocity, 35 feet per minute; load, 500 grams.

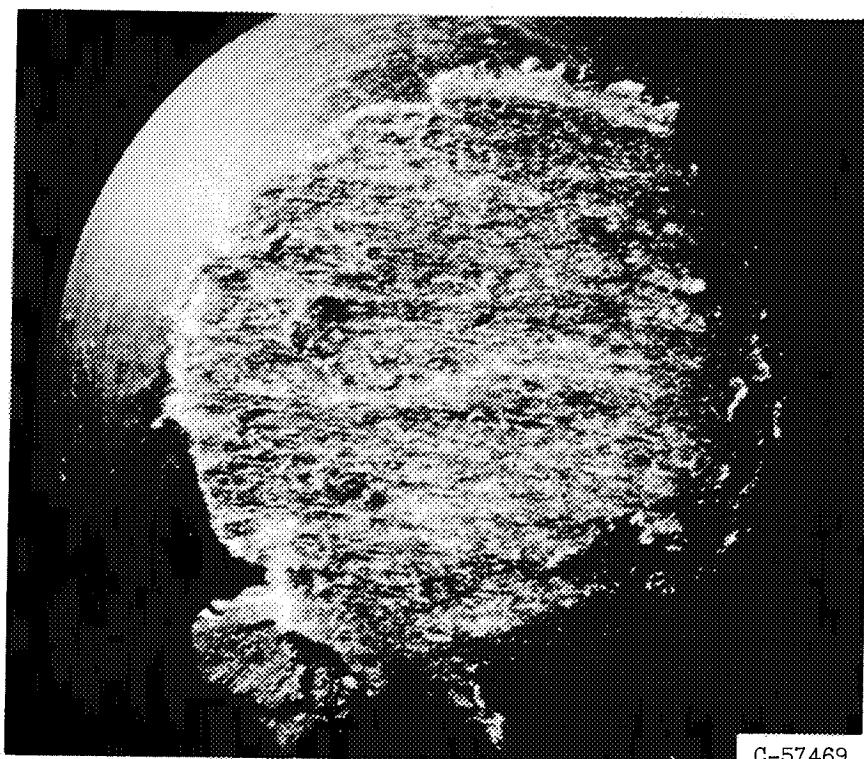
C-55676



E-1343



(a) In air for a duration of 1 hour.



C-57469

(b) In forming gas for a duration of 30 minutes.

Figure 9. - Rider wear areas of copper at 1000° F. Sliding velocity, 35 feet per minute; load, 500 grams.

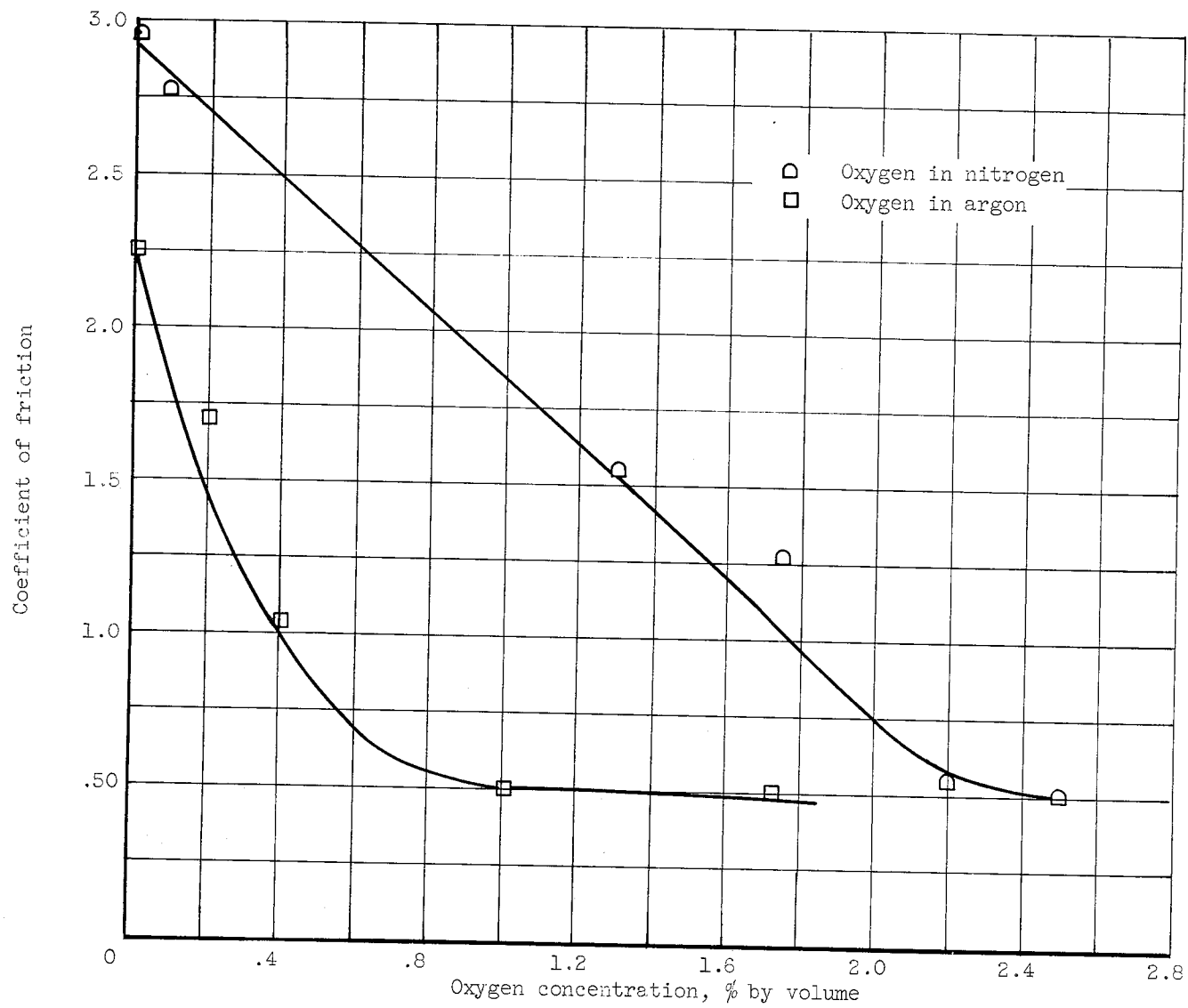


Figure 10. - Coefficient of friction for electrolytic copper sliding on electrolytic copper at 1000° F in various atmospheres. Sliding velocity, 35 feet per minute; load, 500 grams; duration, 1 hour.

<p>NASA TN D-1103 National Aeronautics and Space Administration. EFFECT OF INERT, REDUCING, AND OXIDIZING ATMOSPHERES ON FRICTION AND WEAR OF METALS TO 1000° F. Donald H. Buckley and Robert L. Johnson. October 1961. 26p. OTS price, \$0.75. (NASA TECHNICAL NOTE D-1103)</p> <p>Friction and wear characteristics were studied for various bearing metals in inert, reducing, and oxygen controlled atmospheres at temperatures to 1000° F. A hemispherically tipped rider (3/16-in. rad.) under a 1000-gram load slid on a rotating disk at a surface speed of 35 feet per minute. The absence of oxides on metal surfaces resulted in excessive wear and high friction of metals. In some instances where surfaces were devoid of oxides (electrolytically pure copper), mass welding of the specimens occurred. The presence of extremely small quantities of oxygen (in the atmosphere) for some metals (0.03 volume percent O₂ for 440-C stainless steel) was found to be</p> <p>Copies obtainable from NASA, Washington (over)</p>	<p>I. Buckley, Donald H. II. Johnson, Robert L. III. NASA TN D-1103</p> <p>(Initial NASA distribution: 15, Chemistry, physical; 26, Materials, other.)</p> <p>NASA</p>	<p>NASA TN D-1103 National Aeronautics and Space Administration. EFFECT OF INERT, REDUCING, AND OXIDIZING ATMOSPHERES ON FRICTION AND WEAR OF METALS TO 1000° F. Donald H. Buckley and Robert L. Johnson. October 1961. 26p. OTS price, \$0.75. (NASA TECHNICAL NOTE D-1103)</p> <p>Friction and wear characteristics were studied for various bearing metals in inert, reducing, and oxygen controlled atmospheres at temperatures to 1000° F. A hemispherically tipped rider (3/16-in. rad.) under a 1000-gram load slid on a rotating disk at a surface speed of 35 feet per minute. The absence of oxides on metal surfaces resulted in excessive wear and high friction of metals. In some instances where surfaces were devoid of oxides (electrolytically pure copper), mass welding of the specimens occurred. The presence of extremely small quantities of oxygen (in the atmosphere) for some metals (0.03 volume percent O₂ for 440-C stainless steel) was found to be</p> <p>Copies obtainable from NASA, Washington (over)</p>	<p>I. Buckley, Donald H. II. Johnson, Robert L. III. NASA TN D-1103</p> <p>(Initial NASA distribution: 15, Chemistry, physical; 26, Materials, other.)</p> <p>NASA</p>
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